

SURFACE AND ATMOSPHERIC PARAMETER RETRIEVAL FROM AVIRIS DATA: THE IMPORTANCE OF NON-LINEAR EFFECTS

Jose F. Moreno^(*) and Robert O. Green
Jet Propulsion Laboratory, MS 300-243
4800 Oak Grove Drive, Pasadena, CA 91109-8099
Tel. 818-3543865, Fax: 818-3936943, Email: moreno@blacks.jpl.nasa.gov

^(*) on leave from: Remote Sensing Unit - Faculty of Physics, University of Valencia,
46100 Burjassot, Valencia, Spain

1. INTRODUCTION

AVIRIS data represent a new and important approach for the retrieval of atmospheric and surface parameters from optical remote sensing data. Not only as a test for future space systems, but also as an operational airborne remote sensing system, the development of algorithms to retrieve information from AVIRIS data is an important step to these new approaches and capabilities. Many things have been learned since AVIRIS became operational, and the successive technical improvements in the hardware and the more sophisticated calibration techniques employed have increased the quality of the data to the point of almost meeting optimum user requirements.

However, the potential capabilities of imaging spectrometry over the standard multispectral techniques have still not been fully demonstrated. Reasons for this are the technical difficulties in handling the data, the critical aspect of calibration for advanced retrieval methods, and the lack of proper models with which to invert the measured AVIRIS radiances in all the spectral channels. To achieve the potential of imaging spectrometry, these issues must be addressed.

In this paper, an algorithm to retrieve information about both atmospheric and surface parameters from AVIRIS data, by using model inversion techniques, is described. Emphasis is put on the derivation of the model itself as well as proper inversion techniques, robust to noise in the data and an inadequate ability of the model to describe natural variability in the data. The problem of non-linear effects is addressed, as it has been demonstrated to be a major source of error in the numerical values retrieved by more simple, linear-based approaches. Non-linear effects are especially critical for the retrieval of surface parameters where both scattering and absorption effects are coupled, as well as in the cases of significant multiple-scattering contributions. However, sophisticated modeling approaches can handle such non-linear effects, which are especially important over vegetated surfaces.

All the data used in this study were acquired during the 1991 Multisensor Airborne Campaign (MAC-Europe), as part of the European Field Experiment on a Desertification-threatened Area (EFEDA), carried out in Spain in June-July 1991.

2. DATA PREPROCESSING STEPS

The AVIRIS Data Facility provides users with spectrally, radiometrically, and geometrically calibrated data, but significant additional processing steps are required by the end user based on the final application. Processing steps are critical, because of the necessity of geometrical registration in order to properly account for solar illumination and viewing geometry in the spectral reflectance modeling, and the presence of some spatial noise in the data (which must be removed before any inversion technique is applied).

Geometric processing includes registration (geocoding), with appropriate resampling if the final output is to be in a cartographic reference. Because of the high stability of the ER-2 platform and the roll-angle compensation of the AVIRIS instrument, geometric registration of AVIRIS data is simple compared to that of other airborne systems. Navigation data for the ER-2 were used for a preliminary geometric correction (including panoramic distortion due to aircraft altitude and scan angle). The result was re-corrected to UTM projection by using a first-degree polynomial warping technique. Because the study area is quite flat (height differences of less than 20 m over the full scene), the additional sophistication required in topographically structured areas is not necessary in our case.

A problem encountered in the retrieval of parameters from AVIRIS data is the presence of some kind of spatial coherent noise pattern. This noise does not become apparent in the original images; however, it turns out to be very significant in the retrieval of some parameters, such as atmospheric water vapor. Removal of this spatial noise is required to interpret spatial variability derived in the resulting water vapor map. Filtering methods have to be used to keep the spatial structure present, while eliminating most of the interfering noise. The approach for removing this noise from the image is similar to that used by Rose (1989). The algorithm works over the power spectrum in the Fourier transform of the image (see Fig. 1). The noise is characterized by systematic spikes. Each spike is modeled as a double Gaussian, and the center position and width of the Gaussians are empirically determined from the

display of the power spectrum by assuming an exponential relationship between the distances of the spike centers to the origin of spatial frequencies, and the widths and amplitudes of the spikes.

A critical problem in the pre-processing of AVIRIS data is the instability in spectral channel positions. Although for recent data this problem has been greatly reduced (Figs. 2 and 3), validation of the spectral calibration is necessary before applying inversion techniques. One spectral sensitivity test is based on the derivation of water vapor maps on a channel-by-channel basis for all the channels included in the spectral range between 850 and 1100 nm. A second-degree polynomial is assumed for surface reflectance in this spectral range and the model applies only over bare soil (dry) areas where no coupling absorption due to liquid water content of vegetation (Fig. 4) is expected to give disturbances (Carrere and Conel, 1993). In principle, the value of water vapor derived from each channel should be always the same (within the range allowed by noise). Systematic tendencies in the retrieved water vapor values (especially overestimation in one edge of the absorption band and underestimation in the other edge of the band) are an indication of spectral shift. The water vapor values can be used to estimate spectral shifts and provide a first-order correction for that. An alternative to these image-based approaches is the use of simultaneous ground measurements of reflectance; however, they are sensitive to other uncertainties, so that image-based auto-calibrations are preferable to provide a temporal series of consistent data.

3. PHYSICAL MODELING OF SURFACE REFLECTANCE AND TRANSFER OF RADIATION THROUGH THE ATMOSPHERE

Atmospheric effects are modeled by using a modified version of the Modtran 2 code (Green et al., 1991). Modifications are related only to computational efficiency, and the physics and parameters used in Modtran are unchanged. Limitations in the atmospheric model are then directly related to the accuracy of Modtran to represent atmospheric processes and the availability of some additional data to model the vertical profile. In the absence of the external measurements, the vertical profile is constrained by the altitude of the target for which the reflectance is derived (Green et al., 1993).

As the model is intended for application over vegetated surfaces, emphasis is placed on the modeling of the vegetation and soil components. The surface reflectance model has been developed by combining independent elements: a model for the spectral reflectance and transmittance of leaves, a model for the reflectance of the soil background, and a model for the canopy structure consisting of leaves over the background (Nilson and Kuusk, 1989; Kuusk, 1994). For the reflectance and transmittance of the leaves, an adaptation of the "prospect" model (Jacquemoud and Baret, 1990) is used. The main advantage of this parameterization is that only three parameters (leaf specific biomass, leaf chlorophyll concentration, and leaf liquid water content) determine the spectral reflectance and transmittance of the leaves over the range 0.4–2.5 μm with reasonable accuracy. For the reflectance of bare soil, the model used starts from the same assumptions as the "soilspect" model (Jacquemoud et al., 1992)—that is, separability between macroscopic morphological structure of the soil (giving angular dependences), assumed to be wavelength independent, and the microscopic optical properties (single scattering albedo), assumed to be wavelength dependent. The difficulties in modeling angular behavior, and, especially, spectral behavior, of bare soil reflectances are well known, and a pragmatic modeling with simple assumptions is all that can be expected for realistic approaches. Trying to cover the most general situations possible, the canopy model developed in this case uses eight parameters to characterize the canopy: leaf-area index (LAI), ground vegetation cover, canopy height, two parameters determining leaf distribution, and three more canopy structural parameters. Some structural and hot-spot effects are included only in first-order scattering contributions, while multiple scattering contributions are calculated by using a discrete-ordinate code (applied to a simplified canopy model to save computation time, as architectural effects have less importance for multiple-scattering contributions). To account for the effects of the direct/diffuse irradiance ratio and to model directional irradiance, the surface reflectance model is coupled with an atmospheric model, which is actually a modification of a part of the 6S code. The atmospheric model provides the irradiance field over the scene as a function of wavelength, as the diffuse/total irradiance ratio is highly dependent on wavelength.

Once the surface and atmospheric models are coupled, measured radiances in AVIRIS channels can be inverted to fit the model and give the full set of required surface and atmospheric parameters to explain the measured radiance values. The model runs with a spectral resolution of 2.5 nm, and full bidirectional effects are considered for each single 2.5-nm channel. After final reflectance is calculated for each 2.5-nm channel, AVIRIS bands are simulated by using a Gaussian filter for each band, with the FWHM given by the specifications for the AVIRIS data being used. The final accuracy depends essentially on the accuracy with which the central band positions are known (see Figs. 2 and 3). For old AVIRIS data, the uncertainty in band center positions was such that the spectral band position was adjusted as a parameter. After 1994, the spectral calibration (see Fig. 3) is precise enough to use the spectral model without additional fitting in spectral shifts.

4. RETRIEVAL OF ATMOSPHERIC AND SURFACE PARAMETERS FROM AVIRIS DATA: A MODEL INVERSION TECHNIQUE

After a theoretical model is available, the second step is the development of an appropriate inversion technique in order to retrieve information from the measured data (Jacquemoud, 1993). The inversion technique is a critical

issue. Three main aspects have to be considered. The first one is that the model will not be able to fit the data perfectly, and that some degree of freedom must be allowed in the inversion method. In this case, we use a multi-resolution constrained method to isolate pixels to which the model does not apply and to obtain more robust estimates from those pixels where the model does apply. The second aspect is the problem of noise in the data. In the case of AVIRIS, two types of noise have to be taken into account: the spatial noise (Rose, 1989; see also Fig. 1) and the problem of knowing the exact spectral position of each channel (see Figs. 2 and 3). The spectral stability being a critical issue, the inversion technique must allow some kind of fine tuning in the center positions of channels (or equivalent recalibration in the measured radiances), so that the model can properly fit the measured data. The third aspect is computational efficiency. Because of the large number of channels and parameters in the model, any optimization becomes critical. The use of first guesses as accurate as possible to start the iterative inversion is critical to decrease the number of iterations needed. In this case, we use semiempirical relationships derived by running the model over typical situations and fitting the results to polynomials, so that first guesses can be easily estimated for initialization of model parameters before inversion. The method used for numerical inversion of the reflectance model is the downhill simplex method, with two limiting conditions: maximum error and maximum number of iterations allowed. This method has been preferred over potentially more powerful algorithms (Smith, 1993) because of computational simplicity and robustness to disturbances.

5. RESULTS: THE IMPORTANCE OF NON-LINEAR EFFECTS

a. atmospheric parameters retrieval

The results obtained for atmospheric water vapor retrieval (Fig. 5) agree with the simultaneous radiosoundings that are available as part of the intensive field campaign in the EFEDA'91 experiment. Radiosoundings were made exactly from the same spatial position as the image shown in Figs. 5, 6, and 7 and were calibrated and quality checked as part of the atmospheric experiment. The problem in the intercomparison with AVIRIS data is the altitude of the radiosoundings. Extrapolation to the highest atmospheric levels requires some modeling by using a standard atmosphere, as the altitude of AVIRIS (20 km) is over the available radiosounding measurements. The correspondence of values is in the order of the experimental errors. Although only atmospheric water vapor has been taken into account in this study, the technique used here can be used to retrieve other atmospheric constituents (Barducci and Pippi, 1995). Retrieval of other atmospheric constituents has not been attempted in this area because, as the area is so flat, no spatial variability is expected. Aerosol concentration is also retrieved by the algorithm, but no rigorous attempt has been made to validate such retrievals because of the insufficient quality of in-situ atmospheric transmittance data available for the area. Intercomparisons between AVIRIS data and simultaneous Differential Absorption Lidar (DIAL) data have been made, but no clear conclusions can be derived from such comparisons because of the different type of data as well as differences in spatial resolution.

b. surface parameters retrieval

The main parameter in which we are interested in this study is the leaf (canopy) water content, as part of a more general project to provide inputs to surface energy balance models by using remote sensing data. Estimated values of canopy water content agree reasonably with ground measurements in the case of low LAI (or low vegetation cover), even when a linear model is used for the retrieval of the amount of water in the leaves. As the LAI increases, the non-linear effects due to multiple scattering contributions (Figs. 8 through 13) and canopy geometry (Fig. 14) start to be significant, and we have found errors as large as case (b) in Table 1. In order to explain such anomalous behavior, we have developed the alternative, more sophisticated method previously described, in which a full non-linear model is used to retrieve simultaneously both LAI and leaf water content as separate contributions to the measured reflectance. The new results require the use of a large spectral window in order to isolate the contribution of water from that of LAI and fractional cover separately. As the spectral window used is enlarged, the problem becomes linked to the variability, and uncertainty, in soil background reflectances for non-dense canopies. In the present algorithm, this effect is compensated by allowing variability in surface reflectance (actually total albedo) as a new free parameter for a given single-scattering albedo contribution for bare soil. In the case of large soil variability, a way to model the single-scattering albedo of the soil as a function of soil composition (still keeping soil roughness as an additional free parameter) must be introduced in the model.

Table 1. Comparison of the retrievals of canopy water content from AVIRIS data and simultaneous ground measurements over two reference corn fields, by using a linear fit to a reference absorption depth and compensation of atmospheric water vapor absorption by using the Modtran 2 radiative transfer code. The extreme case (b) is a clear example of the differences that can be introduced due to non-linear effects of multiple scattering.

	LAI value	Estimated canopy water content (g/m ²)	Measured canopy water content (g/m ²)
(a)	0.87	763	710
(b)	3.31	5728	178

A pending work for the future is the validation of the theoretical model developed, as well as the inversion technique, over areas with more ground-truth data for all the required surface and atmospheric parameters. Improvements in the model are also possible, mainly by incorporating new Modtran versions in the atmospheric module. Because of the recent improvements in the AVIRIS instrument, the advantages of using advanced modeling/inversion techniques will be fully realized when working with new data, instead of the 1991 data used in the present study.

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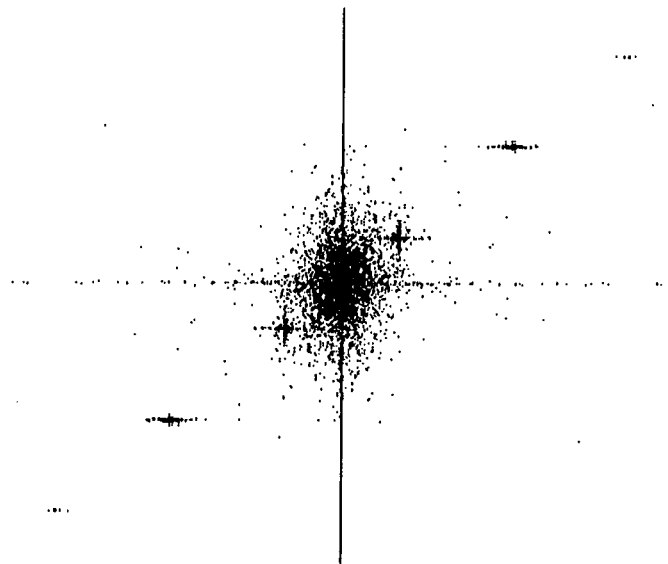


Fig. 1 Fourier power spectrum of the derived spatial water vapor map from AVIRIS data by using a non-linear fit to Modtran-derived radiance and compensation for leaf water absorption. The regular pattern of noise spikes (crosses) along the diagonal causes the spatial interference observed in the original water vapor map, which has been removed in the map shown in Fig. 5.

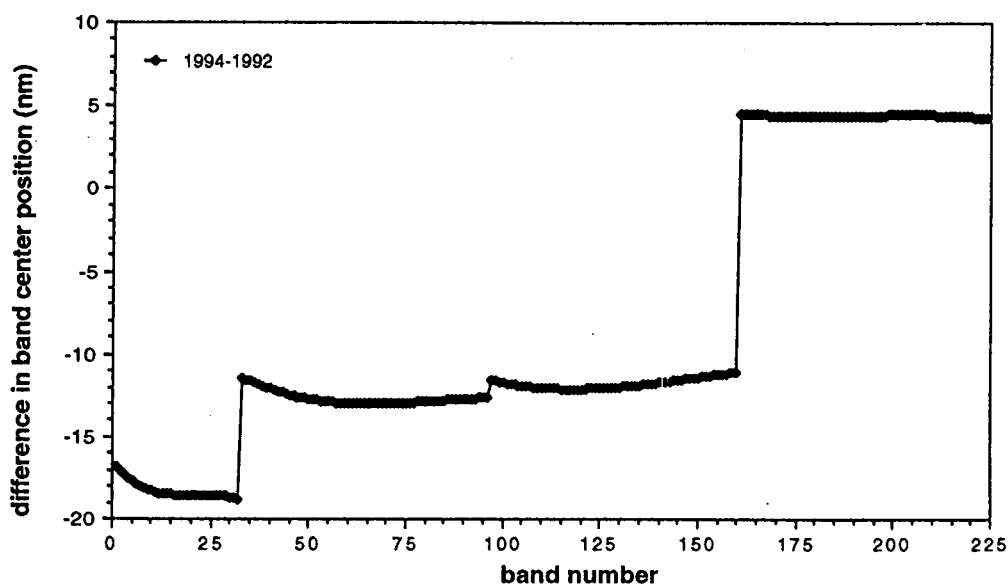


Fig. 2 Difference in AVIRIS band center positions between 1992 and 1994. Changes in the band center positions over time must be accurately known in order to use data inversion techniques based on radiative transfer modeling.

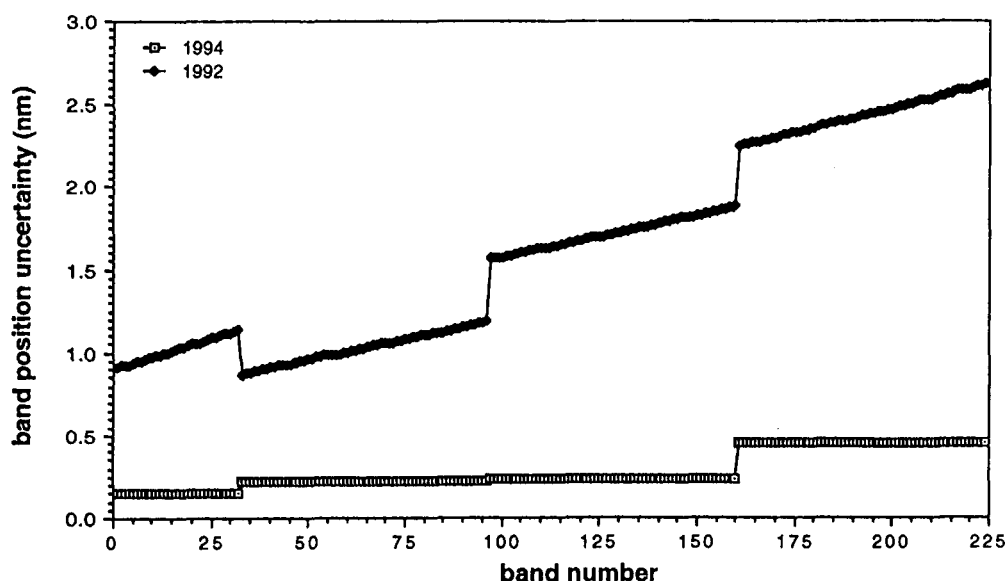


Fig. 3 Uncertainty in band center position, for each AVIRIS channel, for 1992 and 1994 data. Present technical specifications provide data accurate enough to make possible the use of theoretical model-inversion methods which require very precise radiometric and spectral calibrations, with a stability better than 0.5 nm over the full spectral range. Such spectral stability was a major difficulty for old AVIRIS data.

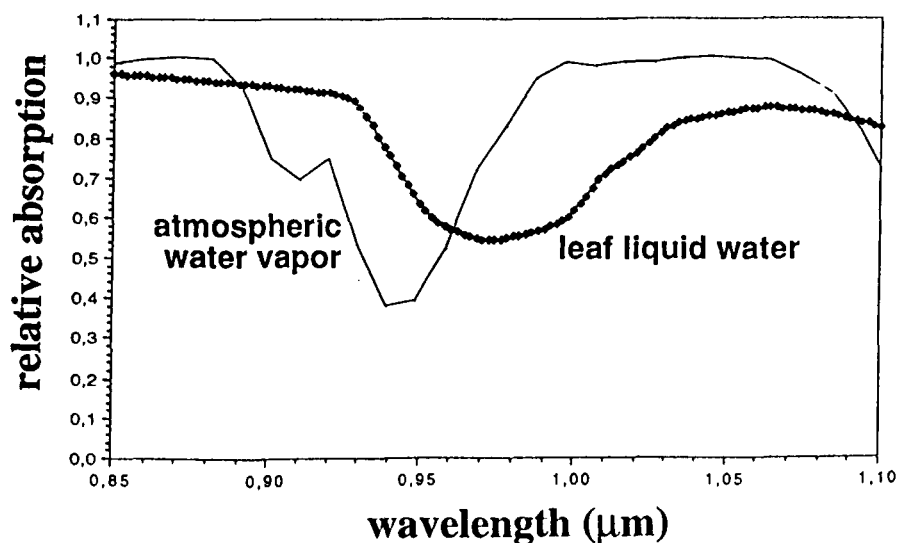


Fig. 4 Coupling of spectral absorption bands for atmospheric water vapor and leaf liquid water in vegetated surfaces. Separation between both absorption components is required to determine accurately atmospheric water vapor, giving also surface liquid water content as residual information.



Fig. 5 Column atmospheric water vapor map derived from AVIRIS for one of the pilot areas of the EFEDA'91 experiment in Central Spain (June 29, 1991), by using a model-inversion technique based on the radiative transfer code Modtran 2.



Fig. 6 Leaf liquid water content derived from AVIRIS data for the same area shown in Fig. 5, obtained as a secondary result in the determination of atmospheric water vapor by non-linear fitting of the shape of the absorption bands (as shown in Fig. 4)

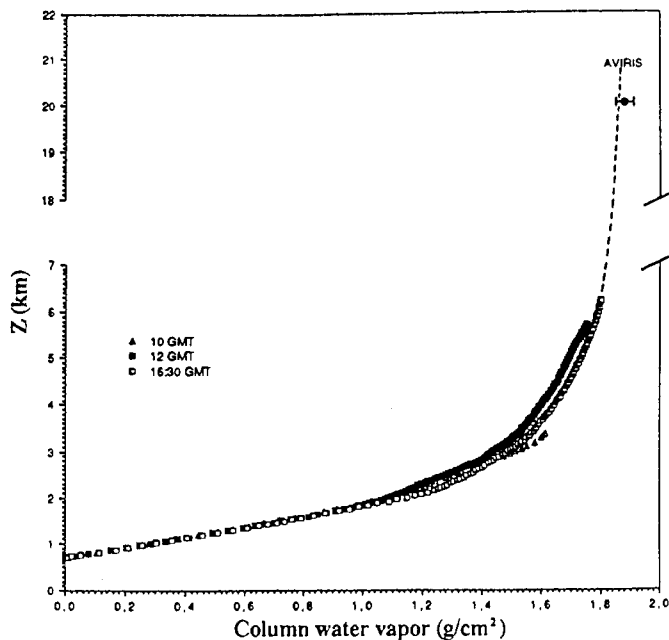


Fig. 7 Comparison between AVIRIS-derived column-integrated atmospheric water vapor content and simultaneous radiosoundings in the area during the EFEDA'91 experiment. The horizontal bar in the AVIRIS-derived value corresponds to the standard deviation within the full scene (about 126 km²).

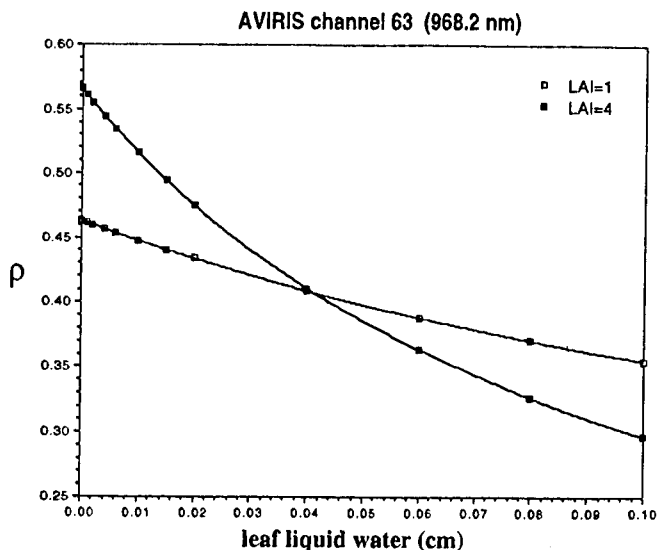


Fig. 8 Relationship between reflectance in AVIRIS channel 63 (the closest to the center of the liquid water absorption band) and leaf liquid water for two values of Leaf Area Index, keeping as constant the rest of the parameters in the model. Differences are essentially due to canopy multiple scattering contributions.

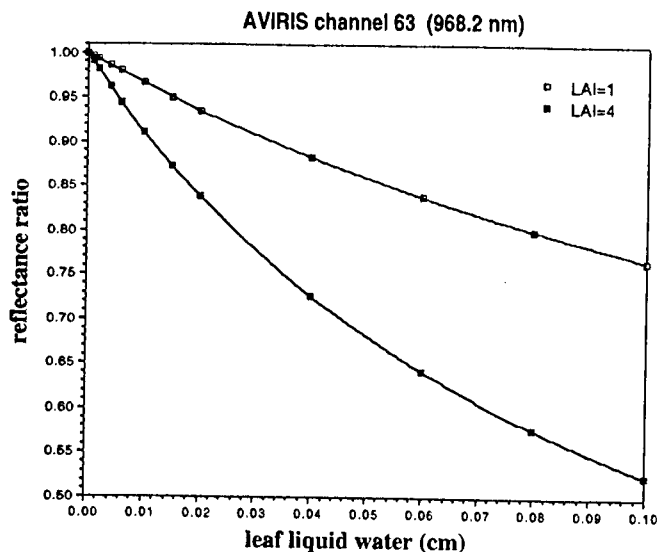


Fig. 9 All the retrievals of liquid water content are somehow based on the ratio between the measured reflectance in the center of the absorption band and the estimated 'maximum' reflectance (in the case of no absorption) for the same other conditions. The changes in this ratio with LAI due to non-linear effects are so important that the retrieved value can vary by more than a factor 3, as in the case illustrated in the figure.

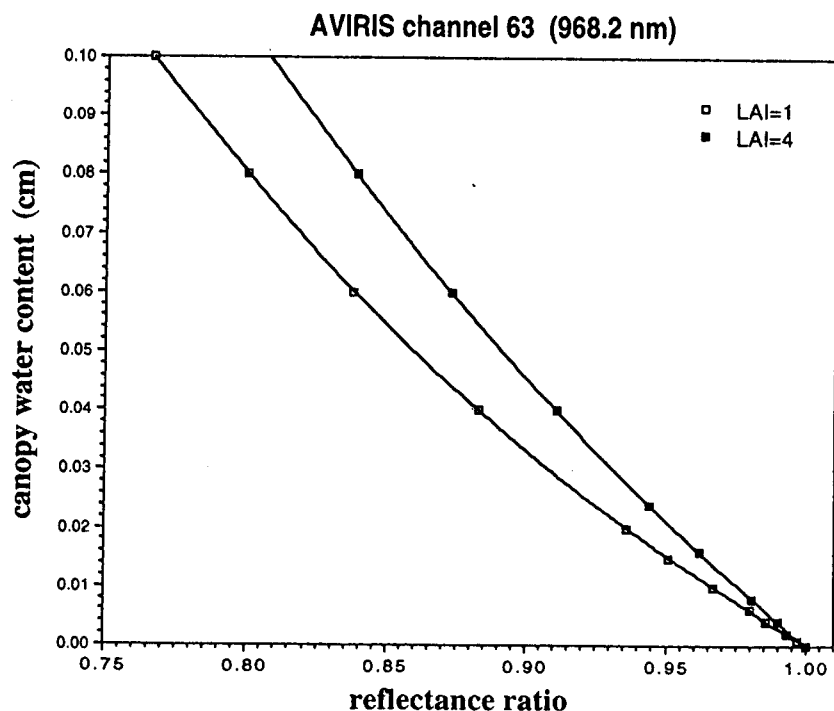


Fig. 10 The same reflectance ratio plotted in Fig. 9, but now as a function of the total canopy water content (LAI*leaf liquid water density). Even when total canopy water is considered, the relationship is still not unique because of non-linear effects.

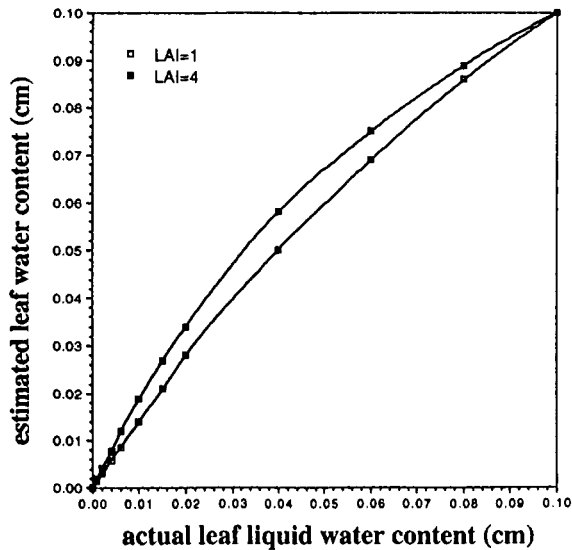


Fig. 11 Comparison between the actual leaf water content and the leaf water content that would be retrieved by using a linear-mixing algorithm (neglecting non-linear effects), but with proper compensation for the 'depth of reference absorption' as a function of LAI. Non-linear effects still produce differences in this case.

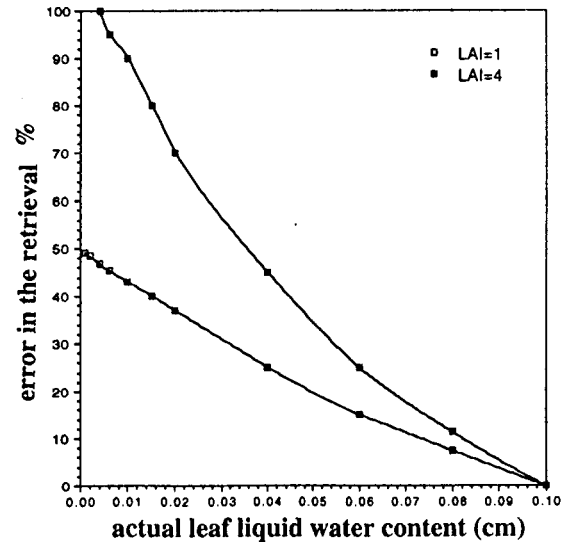


Fig. 12 Relative error in the retrieval of leaf water content by assuming a linear-mixing approach based on 'maximum absorption' features, for two reference LAI values, for the same case shown in Fig. 11.

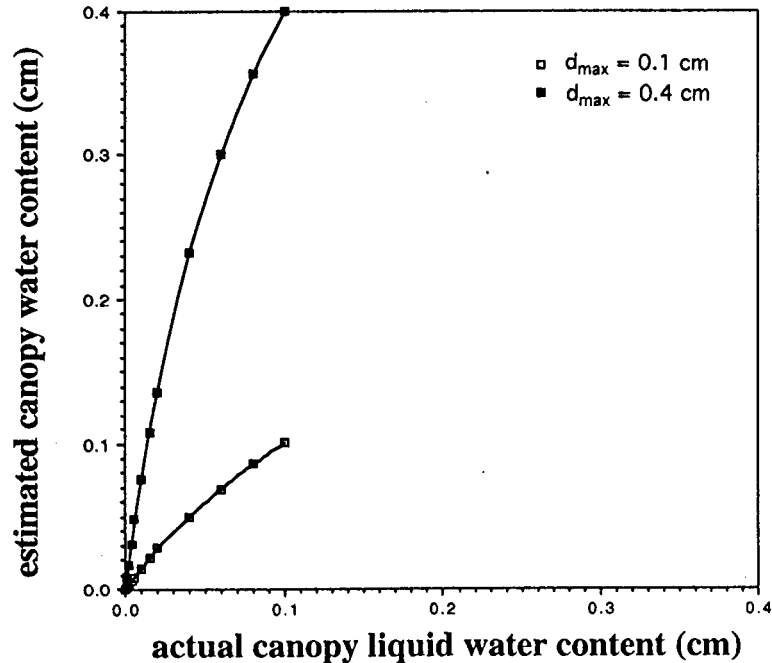


Fig. 13 Comparison between the actual canopy water content and the canopy water content that would be retrieved by using a linear-mixing algorithm (neglecting non-linear effects) and using the 0.4 cm 'depth' absorption as reference, for two values of LAI. The strong overestimation in the case of actually very low water content is the reason for the case (b) shown in Table 1. Errors are actually enhanced because of the coupling to the atmospheric absorption of water vapor and due to the change in the shape of the absorption band with varying LAI.

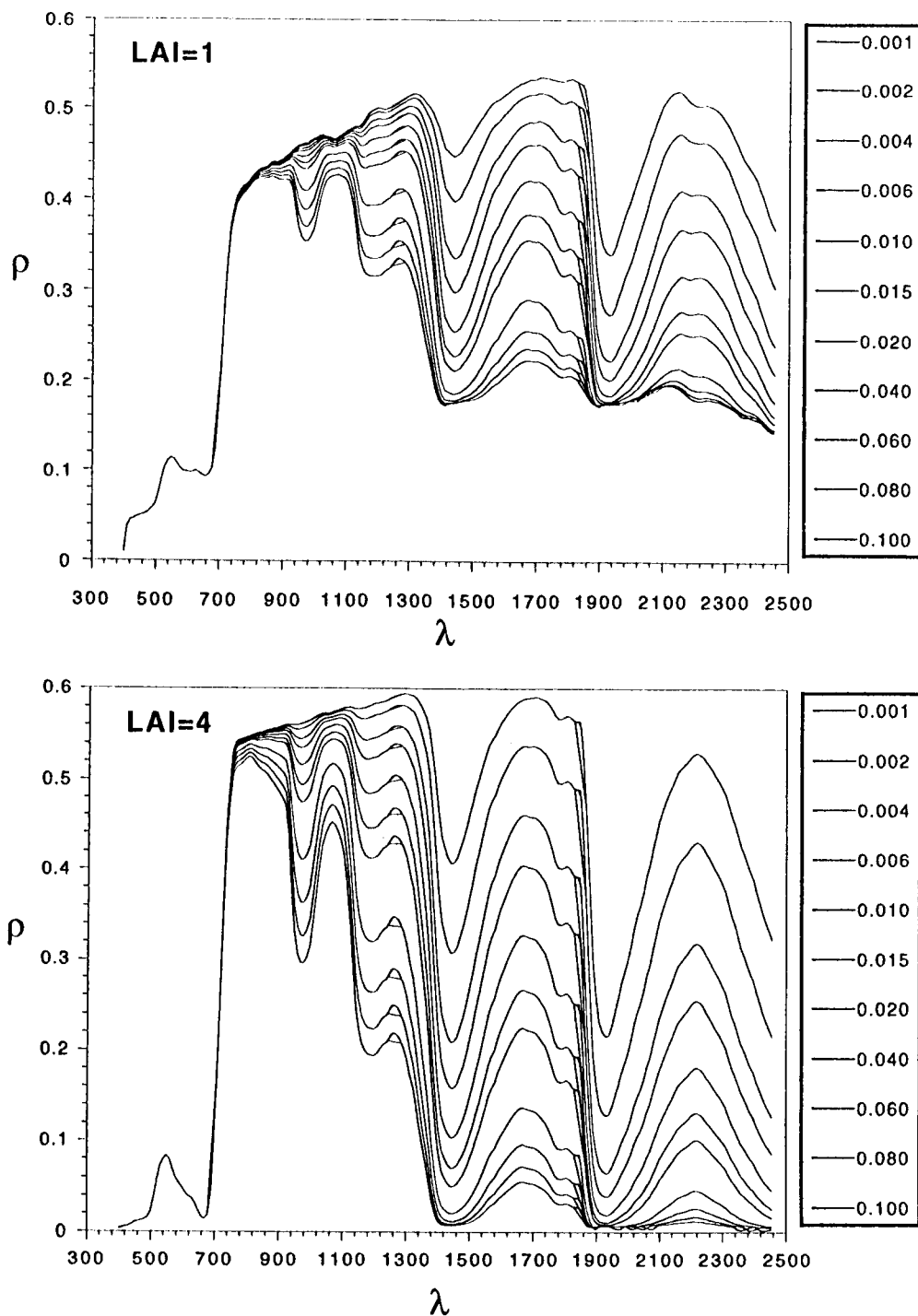


Fig. 14 Simulation of surface reflectance in AVIRIS channels for two different values of Leaf Area Index and several values of leaf water content (numbers on the right column correspond to leaf water content in cm and the order, top-to-bottom, is the same as the curves in both figures). Reflectance values are simulated by a full spectral-bidirectional model, including soil-vegetation multiple scattering, as described in the text. The artifacts appearing around 707 nm, 1286 nm, and 1866 nm are due to the overlaps of channels between adjacent spectrometers, as the simulation is done independently for each AVIRIS channel.